

AGN Feedback in groups and clusters of galaxies

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Abstract. The lack of very cool gas at the cores of groups and clusters of galaxies, even where the cooling time is significantly shorter than the Hubble time, has been interpreted as evidence of sources that re-heat the intergalactic medium. Most studies of rich clusters adopt AGN feedback to be this source of heating. From ongoing GMRT projects involving clusters and groups, we demonstrate how low-frequency GMRT radio observations, together with Chandra/XMM-Newton X-ray data, present a unique insight into the nature of feedback, and of the energy transfer between the AGN and the IGM.

1. Introduction

Simulations of structure formation, using gravitational interactions between dark matter particles, reproduce, to reasonable accuracy, the large-scale properties of the observed web of galaxies and clusters (e.g. Springel et al. 2005). However, when gas physics are added, the simulated galaxies fail to match some of the basic observed properties (e.g., Croton et al. 2005). To produce the observed luminosity function of galaxies, the rate of gas cooling has to be set too high, leading to a severe overestimation of the fraction of baryons in stars, and an underestimate of the fraction in the X-ray emitting gas. Thus, additional sources of heating are required: gravitational heating, supernovae, mergers and conduction are among plausible candidates, but most studies of rich clusters adopt AGN heating to be predominant (see McNamara & Nulsen 2007 and references therein).

The nature of this feedback, vital to our understanding of galaxy and structure evolution, is one of the most important unresolved questions in extragalactic astronomy. In the cores of groups and clusters of galaxies, radiative cooling times are shorter than the Hubble time (see Fig. 1a). Thus, *cooling flows* should result, yet the spectral signature of gas cooling to low temperatures is not seen (Peterson & Fabian 2006). This should be linked to the same source of feedback that is required by the simulations. Furthermore, the raised entropy of the gas within galaxy groups, compared to that expected from scaling cluster properties (“symmetry breaking”), shows evidence of the heating of baryons at modest redshifts before they are assembled into clusters, providing more support for feedback on the scale of galaxies (Ponman, Cannon & Navarro 1999).

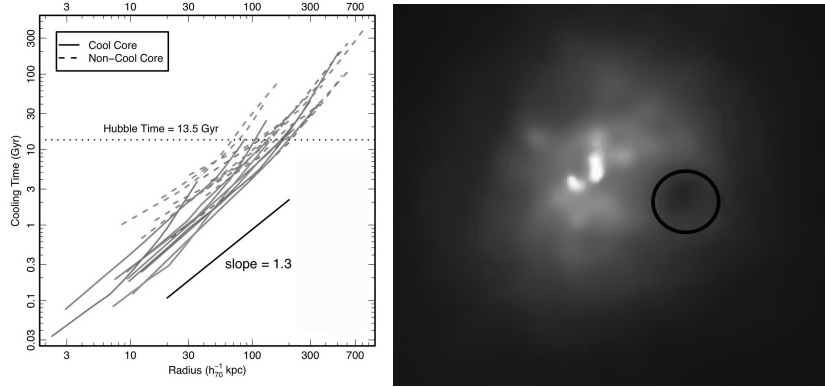


Figure 1. *(a, left)* The cooling time of the X-ray emitting intergalactic medium at the cores of galaxy clusters is less than the Hubble time. The dashed lines represent clusters in which the expected cool core is not found (from Sanderson et al. 2006). This is true of X-ray emitting groups of galaxies as well. *(b, right)* Cavities, created in the IGM as a result of the plasma injected by the central radio source, are confined by the pressure of the IGM. They buoyantly rise through the IGM, transferring a significant part of their enthalpy. Here, in the Chandra X-ray image of the cluster Abell 2597 (McNamara et al. 2001), one such detached (“ghost”) cavity is marked.

2. Observational study of AGN feedback

Most studies of feedback have hitherto focused on AGN jet/cavity systems in the most massive, X-ray luminous galaxy clusters, where the disturbed structures are most clearly seen. However, most galaxies and most of the baryonic matter in the Universe reside in substantially smaller groups, where feedback in principle has the greatest impact on galaxy formation and evolution. It is vital to study feedback in a sample with a wide variety of groups *and* clusters, if we are to understand how feedback has influenced the thermal history of galaxies and the intergalactic medium (IGM), and thus of most of the baryons in the Universe.

2.1. The synergy of X-ray and radio observations

The IGM in groups and clusters emits X-rays, while the relativistic particles from the AGN produce radio emission through synchrotron radiation. However, no simple relation has been established between radio power and the energy required to destroy cool cores. A unified study of observations in multiple wavebands is required to examine the detailed physics of this process of transfer of energy between the AGN and the IGM. The high resolution of the Chandra observatory reveals highly disturbed structures in the cores of many clusters, including shocks, cavities and sharp density discontinuities. Comparing with radio maps, it is clear that AGN jets are associated with many of these disturbances.

The most typical configuration is for jets from the central dominant elliptical of a group or cluster to extend outwards and inflate lobes of radio-emitting plasma, pushing aside the X-ray emitting gas of the cluster halo to create cavities in the hot IGM (Fig. 1b). The enthalpy of a cavity filled with relativistic plasma

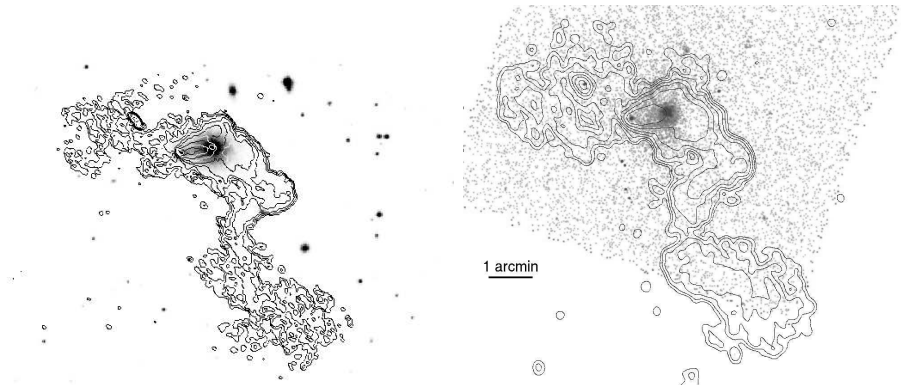


Figure 2. In the NGC 741 fossil group, the jets are emitted from a non-central dwarf galaxy, NGC 742. (a, left) Our 610 MHz GMRT contours, superposed on an optical image, and (b, right) Our 235 MHz GMRT contours, superposed on the 0.5-2 keV Chandra X-ray image, show far more extended radio emission than previous VLA maps. Lowest contours are at 0.15 and 0.9 mJy/beam respectively.

is $4pV$, where p and V are the pressure and volume respectively (McNamara & Nulsen 2007), and a large fraction of this can be transferred to the IGM as the buoyant cavities travel outwards (see, e.g., McNamara & Nulsen 2007, Jethava et al. 2008).

2.2. GMRT studies of galaxy groups

Groups have crucial advantages over richer clusters for studies of feedback – the gas in their relatively shallow potential wells is expected to respond more readily to energy input, and the lower temperature of the IGM would lead to stronger metal emission lines. Our in-depth study of 18 elliptical-dominated galaxy groups, which show structures indicative of AGN interaction in deep Chandra/XMM X-ray images, at 3 GMRT frequencies (235-610 MHz), demonstrates (Vrtilek et al. 2009, O’Sullivan et al. 2009) that by combining deep X-ray and GMRT observations, the extent of the AGN outbursts can be better ascertained, and the chance of detecting earlier outbursts enhanced, than in >1 GHz observations (Giacintucci et al. 2008). These observations (Figs. 2 & 3a) allow one to measure the spectral index as a function of position along the jets, and thus to carefully model the extended emission, and, using equipartition values for the ambient magnetic field, to derive the age of the outburst. This leads to an estimate of the duty cycle of AGN activity, and helps to decouple multiple outbursts, if present. From all of this, in turn, an accurate estimate of the energy of the AGN outburst can be made.

2.3. GMRT studies of feedback in galaxy clusters

Previous studies of feedback in clusters (e.g. Birzan et al. 2004, Dunn et al. 2005, Fabian et al. 2006, McNamara & Nulsen 2007) have concentrated on the core regions of clusters where X-ray images reveal the presence of cavities and related features. To assess how different kinds of radio outbursts contribute to

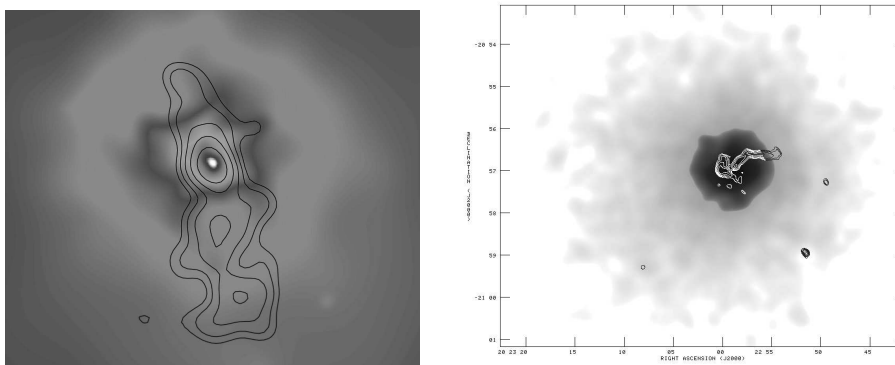


Figure 3. *(a, left)* Smoothed Chandra X-ray image of the HCG 62 compact group of galaxies, in which two ~ 8 kpc cavities are detected. Our GMRT observations (here 235 MHz contours on the Chandra 0.3–2 keV image) show far more extended emission than previous VLA observations (Vrtilek et al. 2002), and evidence of progressive spectral ageing along the jets. *(b, right)* (Preliminary) GMRT 610 MHz contours superposed on the XMM-Newton image of the 2.5 keV REXCESS cluster RXJ2023.0-2056 at redshift $z = 0.056$, showing clear detection of jets associated with the central galaxy.

cluster heating, and how common it is to find AGN activity related to their brightest galaxies, a statistical sample needs to be studied. We have obtained GMRT 610 MHz images of all 26 GMRT-accessible clusters ($z < 0.2$) of the REXCESS sample (Böhringer et al. 2007). Data reduction is in progress: we show a very preliminary map of one of these clusters in Fig. 3b. These clusters have extensive multiwavelength observations (including deep X-ray observations), which we will be able to use in conjunction with the radio observations to model the behaviour of the AGN and its effect on the cluster IGM.

3. Conclusions

The most likely sources of feedback in galaxy groups and clusters are active galactic nuclei. However, the radio power of AGN in central galaxies measured at high radio frequencies is not sufficient to explain the evidence of heating in the IGM of most groups and clusters. Low frequency GMRT observations, along with high-resolution Chandra X-ray observations, are playing a crucial role in the detailed study of the history of AGN outbursts and the mechanism of energy transfer, in an ongoing series of investigations.

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